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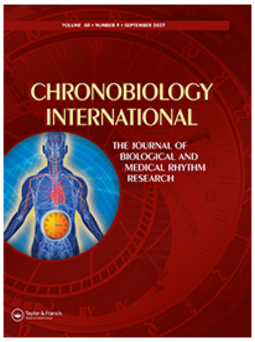

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Is implementing a post-lunch nap beneficial on evening performance, following two nights partial sleep restriction?

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ABSTRACT

We have investigated the effects that partial-sleep-restriction (PSR_0, 4-h sleep retiring at 02:30 and waking at 06:30 h for two consecutive nights) have on 07:30 and 17:00 h cognitive and submaximal weightlifting; and whether this performance improves at 17:00 h following a 13:00 h powernap (0, 30 or 60-min). Fifteen resistance-trained males participated in this study. Prior to the experimental protocol, one repetition max (1RM) bench press and back squat, normative habitual sleep and food intake were recorded. Participants were familiarised with the testing protocol, then completed three experimental conditions: (i) PSR with no nap (PSR_0); (ii) PSR with a 30-min nap (PSR_{30}) and (iii) PSR with a 60-min nap (PSR_{60}). Conditions were separated by 7 days with trial order counterbalanced. Intra-aural temperature, Profile of Mood Scores, word-colour interference, alertness and tiredness values were measured at 07:30, 11:00, 14:00, 17:00 h on the day of exercise protocol. Following final temperature measurements at 07:30 h and 17:00 h, participants completed a 5-min active warm-up before performing three repetitions of left and right-hand grip strength, followed by three repetitions at each incremental load (40, 60 and 80% of 1RM) for bench press and back squat, with a 5-min recovery between each repetition. A linear encoder was attached perpendicular to the bar used for the exercises. Average power (AP), average velocity (AV), peak velocity (PV), displacement (D) and time-to-peak velocity (tPV) were measured (MuscleLab software) during the concentric phase of the movements. Data were analysed using general linear models with repeated measures. The main findings were that implementing a nap at 13:00 h had no effect on measures of strength (grip, bench press or back squat). There was a main effect for time of day with greatest performance at 17:00 h for measures of strength. In addition to a significant effect for "load" on the bar for bench press and back squat where AP, AV, PV, D values were greatest at 40% ($P < 0.05$) and decreased with increased load, whereas tPV and RPE values increased with load; despite this no interaction of "load and condition" were present. A post lunch nap of 30- and 60-minute durations improved mood state, with feelings of alertness, vigour and happiness highest at 17:00 h, in contrast to confusion, tiredness and fatigue ($P < 0.05$), which were greater in the morning (07:30 h). The word-colour interference test, used as an indicator of cognitive function, reported significant main effect for condition, with the highest total test score in PSR_{60} condition ($P = 0.015$). In summary, unlike strength measures the implementation of a 30 or 60-minute nap improved cognitive function when in a partially sleep restricted state, compared to no nap.

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power output; diurnal variation; linear encoder; power lifting; core body temperature; cognitive ability

Introduction

Partial sleep restriction (restricted but not complete elimination of habitual sleep within a 24 h period), is a common occurrence in our society, with 45% of the western population failing to obtain the recommended 7–9 h per night (Bambaeichi et al. 2005; Craven et al. 2022). Athletes are more susceptible to poor sleep quality and duration due to several constraints (such as training/competition demands; time-zone transition disturbing circadian rhythms; psychological issues or environmental factors), achieving an average of 6.5–6.7 h per night (Craven et al. 2022; Sargent et al. 2014; Simpson et al. 2017; Walsh et al. 2021). Due to the fundamental importance of the sleep-wake cycle, circadian rhythm disturbances can be detrimental on physiological and psychological measures, and likely hinder cognitive and some components of sporting performance, with greater deterioration the more sleep loss is accumulated (Reilly and Edwards 2007; Souissi et al. 2008).

The consequences of cumulative sleep loss on performance and cognitive function have been extensively investigated (Thun et al. 2015), and to a lesser extent so have some measures of sporting performance (Leeder

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et al. 2012; Walsh et al. 2021). However, the effectiveness of interventions to combat sleep loss are conflicting, mainly due to the amount (% loss compared to habitual) and timing of sleep restriction (i.e. late bedtime, early rising) that studies employ (Brotherton et al. 2019). Regarding muscular strength, Meney et al. (1998) reported that one night of total sleep restriction resulted in no negative effect on maximal hand grip, leg or back strength. However, Reilly and Deykin (1983) partially restricted sleep for three consecutive nights (2.5 h per night) and reported effects on psychomotor function on the first night, with hand grip strength being affected on the third night. This suggests that when partial sleep loss is employed over multiple nights, impairments on weightlifting performance are more pronounced on the second and third day of sleep loss; suggesting tasks that require greater activation and of larger muscle groups, are more susceptible to sleep loss (Bambaeichi et al. 2005; Reilly and Piercy 1994; Thun et al. 2015). Gross muscular tasks that require less "time on task" are least affected by partial sleep restriction, due to the temporary effort required; in contrast extended tasks or those of a repetitive nature such as Wingate's or sprints are affected to a greater degree (Brotherton et al. 2019; Waterhouse et al. 2007). Due to the high cognitive demand required to execute skill-based tasks, they have shown to be more sensitive under conditions of partial sleep loss, altering mood states and numerous markers of cognitive functions, such as reaction time, alertness, attention and decision making (Durmer and Dinges 2005; Lim and Dinges 2010). Decreases in mood states are also associated with poor motivation, which can consequently impact performance outcomes (Reilly et al. 1997); it is important to note however that cognitive deficit following sleep loss can differ substantially based on interindividual factors, such as chronotype, a person's natural predisposition to be awake or asleep at certain times (Durmer and Dinges 2005; Stolarski et al. 2021). Research indicates that chronotypes may have difference in optimal time points for task execution. These differences along with an increase in homeostatic pressure and accumulation of sleep propensity over the course of a day, signifies the importance of scheduling for exercise sessions, to ensure optimal performance outcomes (Jarraya et al. 2013).

Diurnal fluctuations in physiological functions such as temperature, sleep propensity and alertness are known to heavily influence sporting performance. Studies that have investigated short duration performances (gross muscular power and sprints) have reported greater performance outcomes in the afternoon compared to the morning, due to body temperature peaking between 16:00 and 20:00 h and reaching minimum values between 03:00 and 05:00 h (Edwards et al. 2021; Mills 1966; Williamson and Friswell 2011). Anaerobic activities, such as maximal weightlifting, that last <6 seconds are reported to be 1.9–11.6% greater between 17:00 and 19:00 h; this time-of-day peak was also present in activities lasting 30 seconds to 2 minutes in duration. Tests commonly used to measure anaerobic capacity (Wingate tests, running and cycling repeated sprint bouts) often present variable results, solely due to differences in mode of exercise, protocol employed, fitness levels and motivation of the athlete (Pullinger et al. 2014; Ravindrakumar et al. 2022).

A possible intervention strategy to combat the adverse effects of sleep loss is the implementation of a "nap", a safe and non-invasive intervention that can help increase total sleep time over the 24 h period. It has been reported that 43% of athletes already use some form of napping, however timing of the nap can be very difficult due to the training and competition schedules (Lastella et al. 2015; Romyn et al. 2018). Literature suggests that an afternoon nap between 13:00–15:00 h, lasting between 30–60 minutes in duration should be encouraged, as this is when there is a transient fall in alertness. From 13:00–15:00 h, core temperature values decrease and fatigue ratings rise, and this is also a convenient time of day in an athletes' daily schedule (Brotherton et al. 2019; Waterhouse et al. 2007). Although there is not yet an "optimal" nap duration recommended, many studies suggest 30 minutes to be the most beneficial, with longer nap periods producing sleep inertia, which may require >2 h to recover (Brooks and Lack 2006; Souissi et al. 2020; Waterhouse et al. 2007).

Therefore, the purpose of the present study was to: (1) determine the physiological and psychological effects on muscle strength measures when partially sleep restricted (4 h per night, over two consecutive nights). As well as changes in mood state, cognitive abilities, intra-aural temperature, tiredness, sleepiness and alertness subjective values. (2) To investigate the effectiveness of a 30 *vs* 60-minute post lunch nap, and whether it would improve evening physiological and subjective psychological measures. It was hypothesised that the 60-minute nap opportunity would correspond to greater performance at 17:00 h (physiological and cognitive) compared to 30 minutes or no nap, following two nights of consecutive sleep restriction. Our second hypotheses were that subjective values of alertness and tiredness and cognitive abilities would be impacted to a greater degree in the no nap compared to nap condition.

Methods

Participants

Fifteen males, as identified by sex and gender (mean ± SD: 22 ± 1.59 years; body mass: 79.4 ± 10.4 kg; height: 177.0 ± 5.7 cm; normative retiring and rising times 10:45 ± 0:47 h:min and 07:58 ± 1:18 h:min, respectively), participated in the study. All participants were injury-free with no diagnosed sleep disorders and had not completed shiftwork or travelled outside the local time-zone in the past month. All participants had 1–2 years of strength and weight training experience and were recreationally active, as classified by the "Participant Classification Framework" (McKay et al. 2021). Prior to participating in the study, participants were presented with an information sheet followed by a physical activity readiness questionnaire (PARQ; Chisholm et al. 1975) and a written consent form. Verbal explanation of the experimental procedure was provided; this included the aims of the study, the possible risks associated with participation and the experimental procedures to be utilised. All participants had to express no preference to training regarding time of day. The circadian chronotype of the participants was assessed using a "Composite Morningness/Eveningness Questionnaire" by Smith et al. (1989). The participants' mean "chronotype" score on a 13–52 scale was 33 ± 4; hence, all of the participants were classed as "intermediate types". All participants gave their written informed consent. The experimental procedures were approved by the Human Ethics Committee at Liverpool John Moores University. The study was conducted in accordance with the ethical standards of the journal and complied with the Declaration of Helsinki.

Research design

Each participant attended the laboratory on seven occasions (dry temperature of 19°C, 35–45% humidity and a barometric pressure of 750–760 mmHg, respectively). All participants completed (i) a 5-day habitual food diary, 7-day habitual sleep recording using actimetry (Motionwatch 8, CamnTech), as well as completion of a sleep diary as a secondary measure. The habitual sleep recording was conducted two weeks prior to the first experimental condition, to ensure all participants were maintaining healthy sleep habits before beginning testing. Thereafter each participant completed, (ii) one repetition max (1RM), defined as the maximal weight that can be lifted once while maintaining correct technique (Kraemer et al. 1995), for bench press and back squat, and (iii) two familiarisation sessions. There was a 7-day period between the 1RM session and both familiarisation sessions, to allow adequate recovery. Each familiarisation consisted of an active warm up (full details are given in the measurement section) and completed three repetition lifts at 40, 60, and 80% 1RM for bench press and back squat (see Figure 1 and measurement section for detail). The first familiarisation session involved collection of each participants age, body mass and height, followed by a composite morningness/eveningness questionnaire; this provided insight of sleep and activity preference. Following completion of the final familiarisation there was another 7-day period before commencing the first condition. (iv) The three experimental conditions involved two nights of sleep taken at the participants home before entry into the laboratory on the third day. All participants were partially sleep restricted for two nights and were required to complete all 3 conditions in a counterbalanced order of administration. Participants were allocated into three groups (named 1, 2 and 3) equally based on physical ability for first, second and third session allocation. Practically this entailed stacking each participant 1 RM values for bench press and back squat from heaviest to lightest in Microsoft Excel, then pasting the number 1, 2, 3 to columns respectively so the first cell (strongest participant) was 1 and next was 2, and so on, all the way down the column. The experimental sessions were then counterbalanced in order of administration to minimise any potential learning effects (Monk and Leng 1982). Experimental conditions consisted of retiring to sleep at 02:30 and rising at 06:30 h, and either followed (PSR_0) no nap, (PSR_{30}) 30-min nap at 13:00 until 13:30 h or (PSR_{60}) 60-minute nap at 13:00 until 14:00 h. When completing the PSR_{30} and PSR_{60} experimental conditions, participants were required to sleep/rest on a bed provided in a dark, quiet room in the university sleep laboratory and were not permitted to get up from the bed until the end of the session. Following the nap conditions (PSR_{30} and PSR_{60}), participants were subjectively asked if they had "napped" following this duration, with some participants stating, "they managed to sleep" and others "rested their eyes." At 13:00 h those in the PSR_0 condition were allowed to undertake free living conditions and were instructed not to nap or exercise. Researchers checked in with participants via direct messages to ensure compliance and participants remained on university campus throughout this time. Before experimental sessions participants were asked to refrain from any vigorous physical

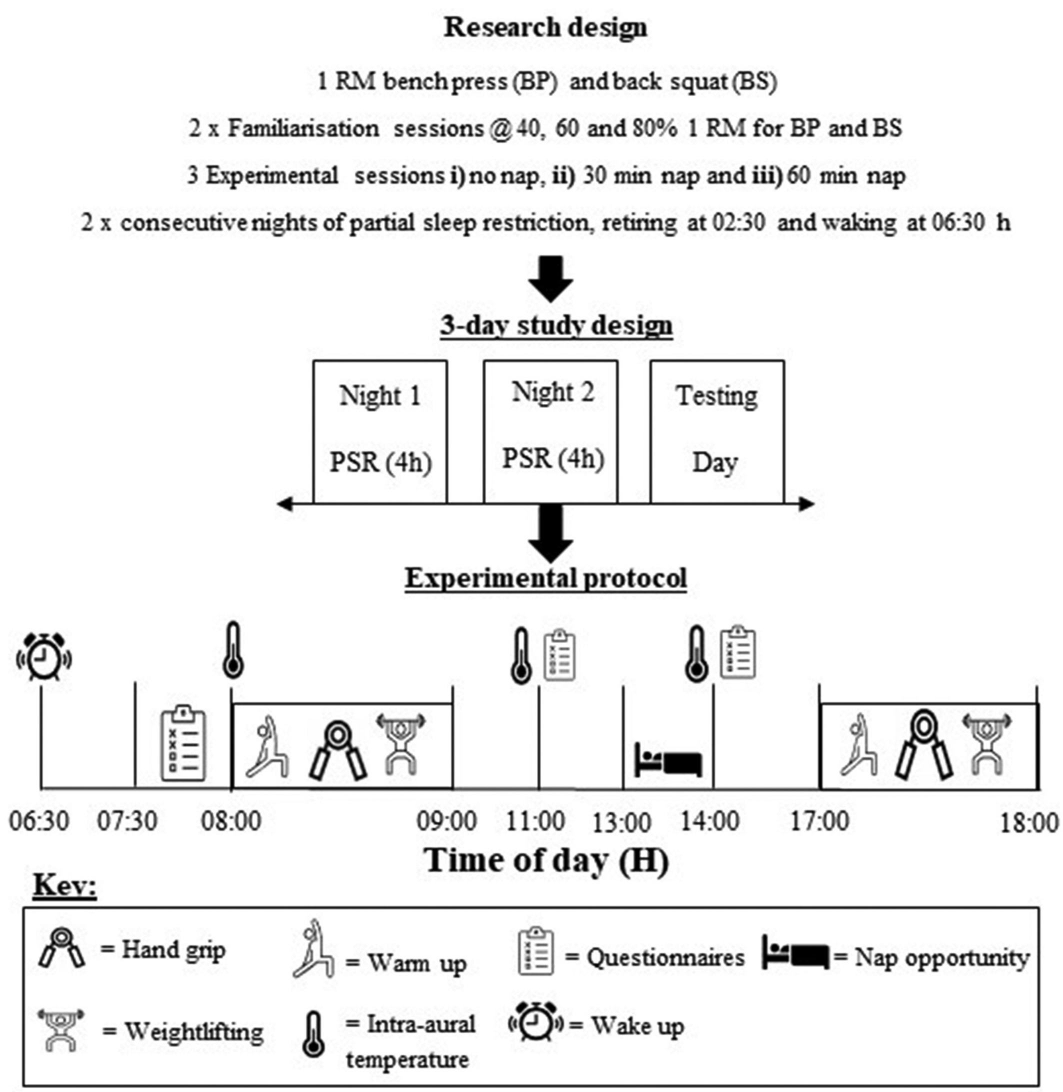

Figure 1. Schematic of experimental protocol. Participants followed the same procedures for each condition, with the addition of a 30 or 60-minute nap at 13:00 h in the PSR_{30} and PSR_{60} conditions. At 07:30 and 17:00 h participants entered the laboratory and undertook the performance measures.

activity 24 h prior, during which time they also had to avoid any alcoholic or caffeine containing drinks. No food was to be consumed 1–2 h before experimental protocol, for both the morning and evening testing session. In the hour before retiring to sleep, participants were asked to refrain from watching television and/or usage of their mobile devices. To ensure recovery between trials there was at least a week between testing conditions for all participants. All experiments were completed between the months of October to May (Autumn to Spring in the UK) with sunrise and sunset range from start to the end of the experiment being 05:37 to 07:29 h and 18:01 to 20:40 h, respectively. Testing was supposed to finish in February to ensure the individual's exposure to sunlight in the mornings when entering the laboratories was < 80 Lux. Unfortunately, due to covid restrictions we had to extend the time frame.

Measurements

Prior to the main experimental laboratory sessions, 1RM sessions determined each participant 1RM percentages for incremental loads of 40, 60 and 80%, allowing a 5-minute recovery between each effort. Familiarisation sessions ensured the participants were physically capable and the risk of failed efforts during bench press and back squat were reduced. Following two consecutive nights of sleep restriction (02:30–06:30 h), participants arrived at the laboratory at 07:30, 11:00, 14:00 and 17:00 h for recordings of intra-aural temperature using a thermometer (Genius 1000, Mark

2, Sherwood, Nottingham, UK); rating of mood (Profile of Mood State questionnaire; McNair and Lorr 1971) and quality of sleep and sleepiness (Stanford Sleepiness Scale; Hoddes et al. 1973). The active warm was performed on a cycle ergometer (Lode Corival, Furth, Germany) at 150 W for 5 minutes, thereafter participants undertook a series of dynamic movements which was repeated twice and involved: Squats (x10), lunges (5 each leg), single leg Romanian deadlifts (5 each leg) and press ups (x10). Post warm-up, participants had three attempts at grip strength with their left and right hand, using a dynamometer (Takei Kiki Kogyo, Tokyo, Japan), the highest reading was taken to represent that time. To prepare for bench press and back squat, the force velocity linear encoder (Muscle Lab, Ergotest version 4010, Norway) was attached to a 20 kg Olympic bar to measure displacement (D), average power (AP), peak power (PV), average velocity (AV) and time-to-peak velocity (tPV) via a laptop. Following grip strength, participants completed bench press and back squat at 40, 60 and 80% of their 1RM, completing three attempts for each incremental load with 5-min rest between each repetition. Sub maximal lifts were recorded using the force transducer; each session performed in the same order of muscle magnitude. At the end of each set for 40, 60 and 80% 1RM, participants gave a value for their rate of perceived exertion on a visual analogue scale (VAS: 0–10, where zero is no effort and 10 is maximal effort; Birk and Birk 1987). As well as rating of perceived exertion, generally and for breathing and muscle fatigue on a 6–20 scale (Borg 1982) for sub maximal lifts completed. The highest of the three AP outputs (and associated AV, PV, D and tPV values) were used for analysis for each mass on the bar for both bench press and back squat, respectively (see Figure 1). A schematic for the experimental protocol is given in Figure 1. Between sessions participants were free to live a "normal life."

Statistical analysis

The Statistical Package for the Social Sciences (SPSS IBM) version 28, for Windows was used. All data were checked for normality using the Shapiro-Wilk test. Differences between conditions were evaluated using a general linear model with repeated measures, within subject factor for nap condition (three levels), within subject factor for time of day (TOD, two or four levels), within subject factor for "load on bar" (three levels) and interactions between all three variables. To correct violations of sphericity, the degrees of freedom were corrected in a normal way, using Huynh-Feldt ($\varepsilon > 0.75$) or Greenhouse-Geisser ($\varepsilon < 0.75$) values for ε, as appropriate. Graphical comparisons between means and Bonferroni pairwise comparisons were made where main effects were present. The α level of statistical significance was set at $P < 0.05$. Effect sizes (ES) were calculated from the ratio of the mean difference to the pooled standard deviation. The magnitude of the ES was classified as trivial (≤0.2), small (>0.2–0.6), moderate (>0.6–1.2), large (>1.2–2.0) and very large (>2.0) based on guidelines from Batterham and Hopkins (2006). The results are presented as the mean ± the standard deviation throughout the text unless otherwise stated. Ninety-five percent confidence intervals are presented where appropriate as well as the mean difference between pairwise comparisons.

Results

Performance measures (measured at 07:30 and 17:00 h)

Mean ± SD values and the results from the ANOVA statistical analysis are displayed in Tables 1 and 2. Statistical significance of the results can be seen in Figures 2 and 3.

Grip strength (left and right hand)

There was no significant effect of nap on left or right-hand grip strength values ($P = 0.211$, $P = 0.176$; respectively, see Table 1). However, there was a significant main effect for time of day for left and right grip strength ($P = 0.018$, $P = 0.05$, see Table 1; respectively), with pairwise comparisons showing greater values at 17:00 compared to 07:00 h for left and right hand (mean difference: 2.00 Nm^{-1}, 95% CI: 0.39–3.61 Nm^{-1}, ES = 0.26: mean difference: 1.58 Nm^{-1}, 95% CI: 0.01–3.15 Nm^{-1}, ES = 0.32, respectively).

Bench press

There was no significant main effect of nap condition for all bench press performance variables (see Table 1). There was a significant main effect for time of day for PV ($P < 0.0005$; see Table 1), where pairwise comparisons showed that participants produced significantly higher PV values in the evening session at 17:00 compared to 07:30 h (1.0 ms^{-1}, $P = 0.001$, 95% CI: 1.0–1.1 ms^{-1} versus 1.0 ms^{-1}, $P = 0.001$, 95% CI: 0.9–1.1 ms^{-1}, ES = 0.62, respectively). No other bench press variables were significant for time of day. There was a significant main effect of "load" for all bench press variables measured (see Table 1). For PV, AP, AV and D, values were highest at 40% 1RM (1.33 ± 0.05 ms^{-1}; 320.0 ± 22.9 W; 0.81 ± 0.02 ms^{-1}; 42.9 ± 1.2 cm, respectively) and lowest at 80% 1RM (0.67 ± 0.04 ms^{-1}; 265.9 ± 14.9 W; 0.58–0.75 ms^{-1} ; 41.8 ± 1.9 cm). Whereas tPV was significantly lower at 40% 1RM (0.33 ± 0.01 ms^{-1}) and highest at 80% 1RM (0.71 ±

Table 1. F values and P values for all performance variables measured in this study ("average power," "average velocity," "displacement," "peak velocity," "time to peak velocity"), rating of perceived exertion (RPE) for both bench press and back squat and perceived effort using the VAS (visual analog scale) for grip strength. **bold** indicates significant ($P < 0.05$); *italic* indicates a trend ($0.1 < p > 0.05$).

Variable	Significance condition	Significance time of day	Significance of load	Interactions (COND * TOD * LOAD)
Grip Strength (N)				
Left	$F_{2.0, 25.8} = 1.66$ ($P = 0.211$)	**$F_{1.0, 13.0} = 6.42$ ($P = 0.025$)**		
Perceived Effort (VAS 0-10)	$F_{2.0, 28.0} = 0.31$ ($P = 0.740$)	$F_{1.0, 14.0} = 0.01$ ($P = 0.919$)		
Right	$F_{1.4, 20.0} = 1.95$ ($P = 0.176$)	**$F_{1.0, 14.0} = 4.61$ ($P = 0.050$)**		
Perceived Effort (VAS 0-10)	$F_{2.0, 28.0} = 0.65$ ($P = 0.531$)	$F_{1.0, 14.0} = 0.58$ ($P = 0.458$)		
Bench Press				
Average Power (W)	$F_{2.0, 28.0} = 1.62$ ($P = 0.215$)	$F_{1.0, 14.0} = 1.34$ ($P = 0.266$)	**$F_{1.3, 17.8} = 14.94$ ($P < 0.0005$)**	$F_{2.0, 27.5} = 0.21$ ($P = 0.806$)
Displacement (cm)	$F_{1.5, 20.9} = 0.70$ ($P = 0.467$)	*$F_{1.0, 14.0} = 4.32$ ($P = 0.056$)*	**$F_{1.6, 22.3} = 6.90$ ($P = 0.007$)**	$F_{2.1, 29.4} = 0.38$ ($P = 0.696$)
Average Velocity (ms^{-1})	$F_{1.5, 21.3} = 1.91$ ($P = 0.179$)	*$F_{1.0, 14.0} = 3.69$ ($P = 0.075$)*	**$F_{1.3, 17.7} = 296.73$ ($P < 0.0005$)**	$F_{2.3, 32.0} = 0.52$ ($P = 0.626$)
Peak Velocity (ms^{-1})	$F_{1.9, 26.7} = 0.28$ ($P = 0.745$)	**$F_{1.0, 14.0} = 16.54$ ($P < 0.0005$)**	**$F_{1.4, 20.2} = 617.66$ ($P < 0.0005$)**	$F_{2.6, 36.1} = 1.20$ ($P = 0.320$)
Time to Peak Velocity (ms^{-1})	$F_{1.6, 22.1} = 0.18$ ($P = 0.786$)	$F_{1.0, 14.0} = 2.59$ ($P = 0.130$)	**$F_{1.1, 15.6} = 59.42$ ($P < 0.0005$)**	$F_{2.8, 39.2} = 0.47$ ($P = 0.695$)
Visual Analog Scale (0–10)	$F_{1.6, 21.9} = 0.92$ ($P = 0.392$)	$F_{1.0, 14.0} = 0.25$ ($P = 0.627$)	**$F_{1.3, 18.7} = 148.42$ ($P < 0.0005$)**	$F_{2.3, 32.2} = 0.82$ ($P = 0.465$)
RPE (6–20)	$F_{2.0, 28.0} = 1.27$ ($P = 0.297$)	$F_{1.0, 14.0} = 1.35$ ($P = 0.265$)	**$F_{1.4, 19.5} = 132.93$ ($P < 0.0005$)**	$F_{2.9, 40.5} = 0.69$ ($P = 0.561$)
RPE Breathing (6–20)	$F_{2.0, 28.0} = 0.09$ ($P = 0.911$)	$F_{1.0, 14.0} = 1.06$ ($P = 0.321$)	**$F_{1.3, 17.9} = 67.96$ ($P < 0.0005$)**	$F_{2.1, 31.1} = 0.35$ ($P = 0.727$)
RPE Muscle Fatigue (6–20)	$F_{2.0, 28.0} = 1.55$ ($P = 0.230$)	$F_{1.0, 14.0} = 1.23$ ($P = 0.286$)	**$F_{1.3, 17.6} = 175.43$ ($P < 0.0005$)**	*$F_{2.9, 40.2} = 2.39$ ($P = 0.086$)*
Back Squat				
Average Power (W)	$F_{1.9, 25.9} = 0.12$ ($P = 0.873$)	*$F_{1.0, 14.0} = 4.44$ ($P = 0.054$)*	**$F_{1.2, 17.4} = 54.88$ ($P < 0.0005$)**	$F_{3.1, 44.0} = 1.43$ ($P = 0.247$)
Displacement (cm)	$F_{2.0, 28.0} = 1.65$ ($P = 0.210$)	$F_{1.0, 14.0} = 0.52$ ($P = 0.483$)	**$F_{1.2, 16.8} = 5.30$ ($P = 0.029$)**	$F_{3.3, 45.8} = 0.33$ ($P = 0.819$)
Average Velocity (ms^{-1})	$F_{2.0, 28.0} = 1.03$ ($P = 0.372$)	**$F_{1.0, 14.0} = 5.54$ ($P = 0.034$)**	**$F_{1.1, 16.0} = 182.95$ ($P < 0.0005$)**	$F_{2.6, 37.1} = 1.80$ ($P = 0.170$)
Peak Velocity (ms^{-1})	$F_{2.0, 28.0} = 0.21$ ($P = 0.810$)	**$F_{1.0, 14.0} = 8.41$ ($P = 0.012$)**	**$F_{1.2, 16.7} = 110.37$ ($P < 0.0005$)**	$F_{2.0, 28.6} = 0.15$ ($P = 0.865$)
Time to Peak Velocity (ms^{-1})	$F_{1.9, 26.4} = 0.06$ ($P = 0.930$)	$F_{1.0, 14.0} = 0.85$ ($P = 0.372$)	**$F_{1.1, 15.5} = 112.87$ ($P < 0.0005$)**	$F_{2.6, 37.0} = 0.76$ ($P = 0.507$)
Visual Analog Scale (0–10)	$F_{1.8, 25.8} = 0.20$ ($P = 0.805$)	$F_{1.0, 14.0} = 0.37$ ($P = 0.552$)	**$F_{1.2, 16.7} = 249.45$ ($P < 0.0005$)**	$F_{2.8, 38.8} = 0.48$ ($P = 0.687$)
RPE (6–20)	$F_{2.0, 28.0} = 0.19$ ($P = 0.830$)	**$F_{1.0, 14.0} = 6.58$ ($P = 0.022$)**	**$F_{1.5, 20.5} = 218.55$ ($P < 0.0005$)**	$F_{2.9, 40.5} = 0.75$ ($P = 0.523$)
RPE Breathing (6–20)	$F_{2.0, 27.8} = 0.23$ ($P = 0.797$)	$F_{1.0, 14.0} = 0.06$ ($P = 0.812$)	**$F_{1.4, 18.9} = 81.46$ ($P < 0.0005$)**	$F_{3.2, 45.2} = 0.90$ ($P = 0.454$)
RPE Muscle Fatigue (6–20)	$F_{2.0, 28.0} = 1.32$ ($P = 0.284$)	$F_{1.0, 14.0} = 1.12$ ($P = 0.309$)	**$F_{1.5, 21.5} = 232.77$ ($P < 0.0005$)**	$F_{2.5, 34.5} = 1.06$ ($P = 0.369$)

Interactions	COND*TOD	COND*LOAD	TOD*LOAD
Grip Strength			
Left	$F_{2.0, 26.0} = 0.95$ ($P = 0.401$)		
Perceived Effort (VAS 0–10)	$F_{1.9, 26.3} = 0.90$ ($P = 0.415$)		
Right	$F_{2.0, 28.0} = 0.58$ ($P = 0.567$)		
Perceived Effort (VAS 0-10)	$F_{1.4, 19.4} = 0.46$ ($P = 0.570$)		
Bench Press			
Average Power (W)	$F_{1.5, 21.4} = 0.41$ ($P = 0.612$)	$F_{2.3, 32.8} = 0.61$ ($P = 0.575$)	$F_{1.4, 19.6} = 1.16$ ($P = 0.317$)
Displacement (cm)	$F_{1.9, 27.1} = 0.60$ ($P = 0.553$)	$F_{2.7, 38.3} = 1.48$ ($P = 0.238$)	$F_{1.4, 19.5} = 0.67$ ($P = 0.470$)
Average Velocity (ms^{-1})	**$F_{2.0, 28.0} = 3.36$ ($P = 0.049$)**	$F_{2.1, 29.6} = 0.59$ ($P = 0.568$)	$F_{1.5, 20.9} = 2.22$ ($P = 0.144$)
Peak Velocity ($m\ s^{-1}$)	$F_{2.0, 28.0} = 2.12$ ($P = 0.141$)	$F_{2.4, 34.0} = 0.27$ ($P = 0.809$)	$F_{1.2, 17.1} = 1.03$ ($P = 0.342$)
Time to Peak Velocity (s)	$F_{2.0, 28.0} = 0.21$ ($P = 0.811$)	$F_{2.1, 29.0} = 1.40$ ($P = 0.262$)	$F_{1.2, 16.2} = 1.69$ ($P = 0.215$)
Visual Analog Scale (0–10)	$F_{2.0\ 28.0} = 0.56$ ($P = 0.580$)	$F_{2.8, 39.5} = 1.22$ ($P = 0.315$)	$F_{1.5, 21.6} = 0.26$ ($P = 0.716$)
RPE (6–20)	$F_{1.8, 25.4} = 0.46$ ($P = 0.618$)	$F_{2.3, 31.9} = 0.56$ ($P = 0.597$)	$F_{2.0, 28.0} = 0.16$ ($P = 0.855$)
RPE Breathing (6–20)	$F_{2.0, 28.0} = 0.18$ ($P = 0.834$)	$F_{2.7, 37.2} = 0.37$ ($P = 0.749$)	$F_{2.0, 28.0} = 2.80$ ($P = 0.078$)
RPE Muscle Fatigue (6–20)	$F_{1.6, 22.1} = 2.26$ ($P = 0.137$)	$F_{2.3, 32.3} = 0.22$ ($P = 0.835$)	$F_{2.0, 28.0} = 1.26$ ($P = 0.300$)
Back Squat			
Average Power (W)	$F_{1.2, 16.6} = 0.24$ ($P = 0.685$)	$F_{2.3, 32.5} = 1.04$ ($P = 0.372$)	$F_{1.3, 18.1} = 0.40$ ($P = 0.590$)
Displacement (cm)	$F_{1.5, 20.3} = 0.24$ ($P = 0.717$)	*$F_{2.7, 37.8} = 2.50$ ($P = 0.080$)*	$F_{2.0, 28.0} = 1.64$ ($P = 0.212$)
Average Velocity (ms^{-1})	**$F_{1.8, 24.8} = 4.18$ ($P = 0.031$)**	$F_{1.9, 26.9} = 1.05$ ($P = 0.361$)	**$F_{1.4, 19.4} = 4.72$ ($P = 0.032$)**
Peak Velocity (ms^{-1})	$F_{1.5, 20.4} = 0.18$ ($P = 0.765$)	$F_{2.3, 31.8} = 0.84$ ($P = 0.453$)	**$F_{1.2, 16.4} = 6.02$ ($P = 0.022$)**
Time to Peak Velocity (s)	$F_{1.9, 26.6} = 1.62$ ($P = 0.217$)	$F_{2.5, 34.3} = 0.46$ ($P = 0.674$)	**$F_{1.4, 19.6} = 9.16$ ($P = 0.004$)**
Visual Analog Scale (0–10)	$F_{1.4, 19.0} = 1.65$ ($P = 0.218$)	$F_{2.6, 35.8} = 0.87$ ($P = 0.451$)	$F_{2.0, 28.0} = 0.50$ ($P = 0.615$)
RPE (6–20)	$F_{2.0, 27.4} = 2.23$ ($P = 0.127$)	$F_{3.0, 42.4} = 0.83$ ($P = 0.488$)	$F_{1.3, 18.5} = 0.98$ ($P = 0.361$)
RPE Breathing (6–20)	$F_{1.9, 26.1} = 0.00$ ($P = 1.000$)	$F_{2.6, 35.8} = 0.57$ ($P = 0.610$)	$F_{1.1, 15.9} = 0.52$ ($P = 0.503$)
RPE Muscle Fatigue (6–20)	$F_{1.6, 22.0} = 1.51$ ($P = 0.242$)	$F_{2.9, 40.1} = 1.80$ ($P = 0.166$)	$F_{1.6, 21.7} = 0.65$ ($P = 0.492$)

Table 2. Mean ± SD, F values and P values for all physiological and psychological variables measured in the study (temperature, tiredness, alertness, Profile of mood states (POMS), word and colour interference test). **Bold** values indicate significant figures; *italic* indicates a trend ($0.1 < P > 0.05$).

Variables	SD	SD_{30}	SD_{60}	Significance condition	Significance time of day	Significance interaction
Intra-aural Temperature (°C)	35.51 ± 0.14	36.00 ± 0.13	36.15 ± 0.12	**$F_{2.0,\ 28.0} = 11.15$ ($P < 0.0005$)**	**$F_{1.9,\ 27.0} = 6.01$ ($P = 0.007$)**	$F_{3.0,\ 41.4} = 0.99$ ($P = 0.405$)
Tiredness (0–10 VAS)	5.2 ± 0.8	6.2 ± 0.8	6.1 ± 0.7	$F_{2.0,\ 28.0} = 1.42$ ($P = 0.260$)	**$F_{2.39,\ 33.45} = 20.61$ ($P < 0.0005$)**	$F_{2.48,\ 34.65} = 0.35$ ($P = 0.755$)
Alertness (0–10 VAS)	5.7 ± 0.6	5.1 ± 0.7	4.9 ± 0.6	$F_{1.6,\ 22.1} = 1.46$ ($P = 0.252$)	**$F_{3.0.\ 42.0} = 17.46$ ($P < 0.0005$)**	$F_{4.0,\ 56.5} = 0.57$ ($P = 0.685$)
Stanford Sleepiness	3.0 ± 0.3	3.4 ± 0.3	3.4 ± 0.3	*$F_{2.0,\ 28.0} = 2.59$ ($P = 0.097$)*	**$F_{2.1,\ 29.7} = 15.54$ ($P < 0.0005$)**	$F_{3.3,\ 46.0} = 1.18$ ($P = 0.329$)
Mood State-Vigour	6.1 ± 3.6	5.2 ± 3.9	5.3 ± 3.8	$F_{2.0,\ 28.0} = 1.72$ ($P = 0.197$)	**$F_{2.4,\ 34.2} = 18.43$ ($P < 0.0005$)**	$F_{4.3,\ 60.7} = 1.23$ ($P = 0.309$)
Mood State-Anger	1.2 ± 2.2	1.8 ± 0.9	0.9 ± 1.4	$F_{1.4,\ 17.7} = 0.92$ ($P = 0.383$)	$F_{1.4,\ 18.6} = 2.44$ ($P = 0.127$)	$F_{2.4,\ 31.2} = 1.19$ ($P = 0.324$)
Mood State- Tension	0.6 ± 0.2	0.9 ± 0.4	0.7 ± 0.2	$F_{1.4,\ 19.1} = 0.68$ ($P = 0.466$)	$F_{1.4,\ 19.1} = 1.95$ ($P = 0.177$)	$F_{3.4,\ 46.9} = 0.72$ ($P = 0.559$)
Mood State- Calm	5.5 ± 0.7	5.1 ± 0.8	5.0 ± 0.7	$F_{2.0,\ 26.0} = 0.75$ ($P = 0.481$)	$F_{1.9,\ 24.3} = 1.94$ ($P = 0.167$)	$F_{3.3,\ 43.3} = 1.08$ ($P = 0.370$)
Mood State- Happiness	4.9 ± 0.7	4.1 ± 0.7	4.3 ± 0.7	$F_{2.0,\ 26.0} = 0.93$ ($P = 0.407$)	**$F_{2.3,\ 29.8} = 4.98$ ($P = 0.011$)**	$F_{3.9,\ 51.2} = 0.98$ ($P = 0.428$)
Mood State- Confusion	1.3 ± 0.4	1.8 ± 0.6	1.0 ± 0.3	$F_{1.3,\ 16.6} = 1.25$ ($P = 0.293$)	**$F_{1.7,\ 22.5} = 5.51$ ($P = 0.014$)**	$F_{3.4,\ 44.2} = 1.17$ ($P = 0.333$)
Mood State- Depression	1.0 ± 0.4	1.6 ± 0.5	1.0 ± 0.3	$F_{2.0,\ 26.0} = 1.14$ ($P = 0.335$)	*$F_{1.5,\ 19.8} = 2.98$ ($P = 0.085$)*	$F_{3.2,\ 41.4} = 1.26$ ($P = 0.300$)
Mood State- Fatigue	5.6 ± 2.0	6.8 ± 0.9	6.1 ± 0.8	$F_{2.0,\ 28.0} = 1.24$ ($P = 0.305$)	**$F_{2.3,\ 32.4} = 14.54$ ($P < 0.0005$)**	$F_{2.9,\ 40.3} = 0.43$ ($P = 0.726$)
STROOP (Colours/NotW/TOTAL)	60.2 ± 2.3	62.8 ± 2.0	66.8 ± 2.7	**$F_{1.5,\ 21.5} = 5.81$ ($P = 0.015$)**	$F_{1.4,\ 19.1} = 1.66$ ($P = 0.217$)	$F_{2.8,\ 39.8} = 1.13$ ($P = 0.346$)
STROOP (Colours/NotW/ERROR)	1.2 ± 0.2	1.1 ± 0.2	1.1 ± 0.2	$F_{2.0,\ 28.0} = 0.54$ ($P = 0.591$)	**$F_{3.0,\ 42.0} = 2.98$ ($P = 0.042$)**	$F_{3.7,\ 51.5} = 1.28$ ($P = 0.289$)
STROOP (Words/NotC/TOTAL)	105.6 ± 3.9	108.7 ± 4.1	110.5 ± 3.2	**$F_{2.0,\ 28.0} = 3.47$ ($P = 0.045$)**	$F_{2.2,\ 31.0} = 0.85$ ($P = 0.447$)	$F_{4.3,\ 59.9} = 0.38$ ($P = 0.833$)
STROOP (Words/NotC/ERROR)	1.0 ± 0.2	0.7 ± 0.1	0.8 ± 0.2	$F_{2.0,\ 28.0} = 0.87$ ($P = 0.431$)	$F_{2.4,\ 33.0} = 1.35$ ($P = 0.274$)	$F_{3.9,\ 54.5} = 0.34$ ($P = 0.844$)

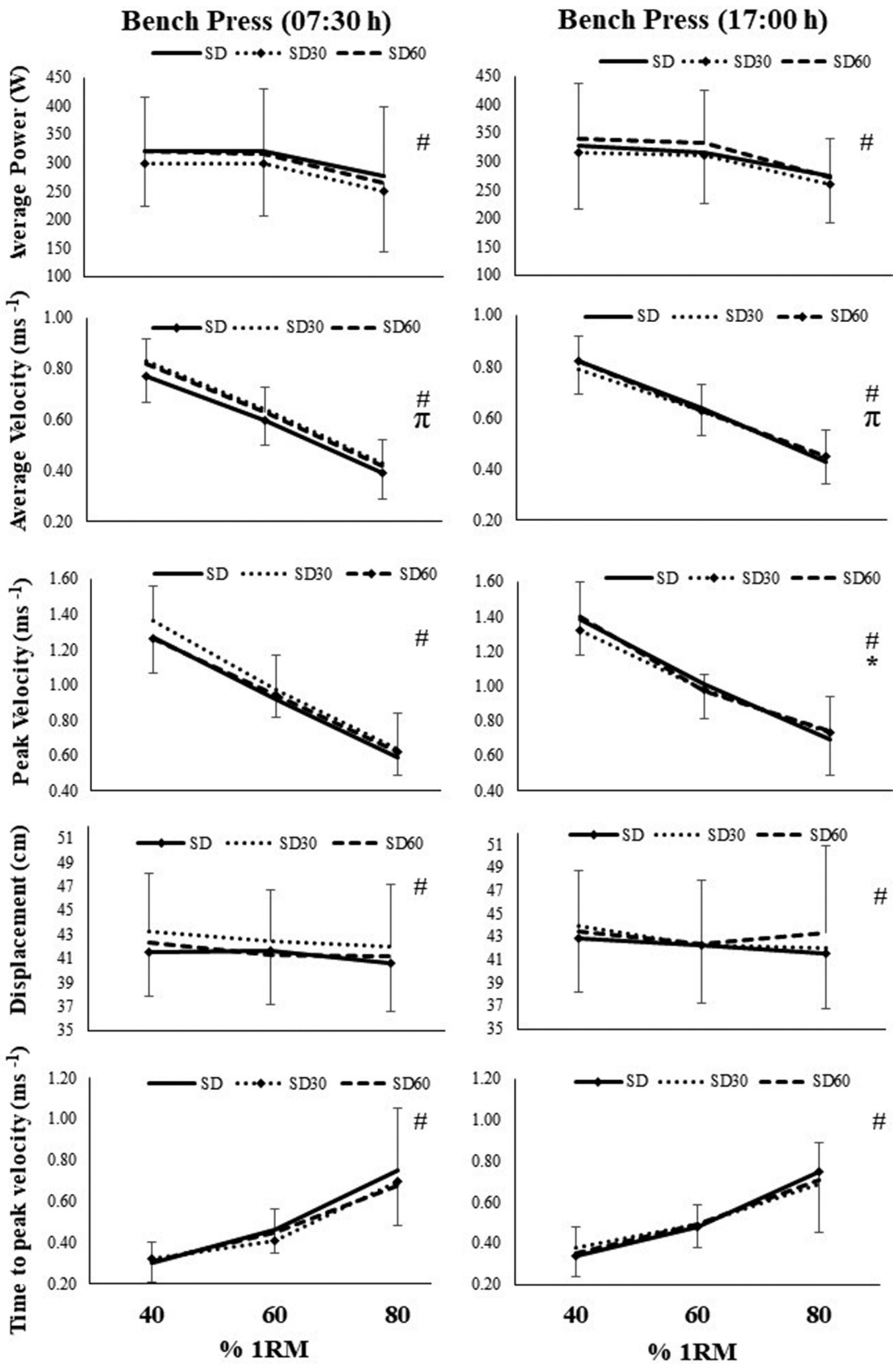

Figure 2. Mean ± SD values of each performance variable for morning (07:30 h) and evening (17:00 h) bench press at 40%, 60% and 80% 1RM loads for the three experimental conditions. # denotes main effect for load, as shown by Bonferroni pairwise comparisons ($P < 0.05$), * denotes main effect for time of day as shown by Bonferroni pairwise comparisons ($P < 0.05$) and π denotes condition and time of day interaction.

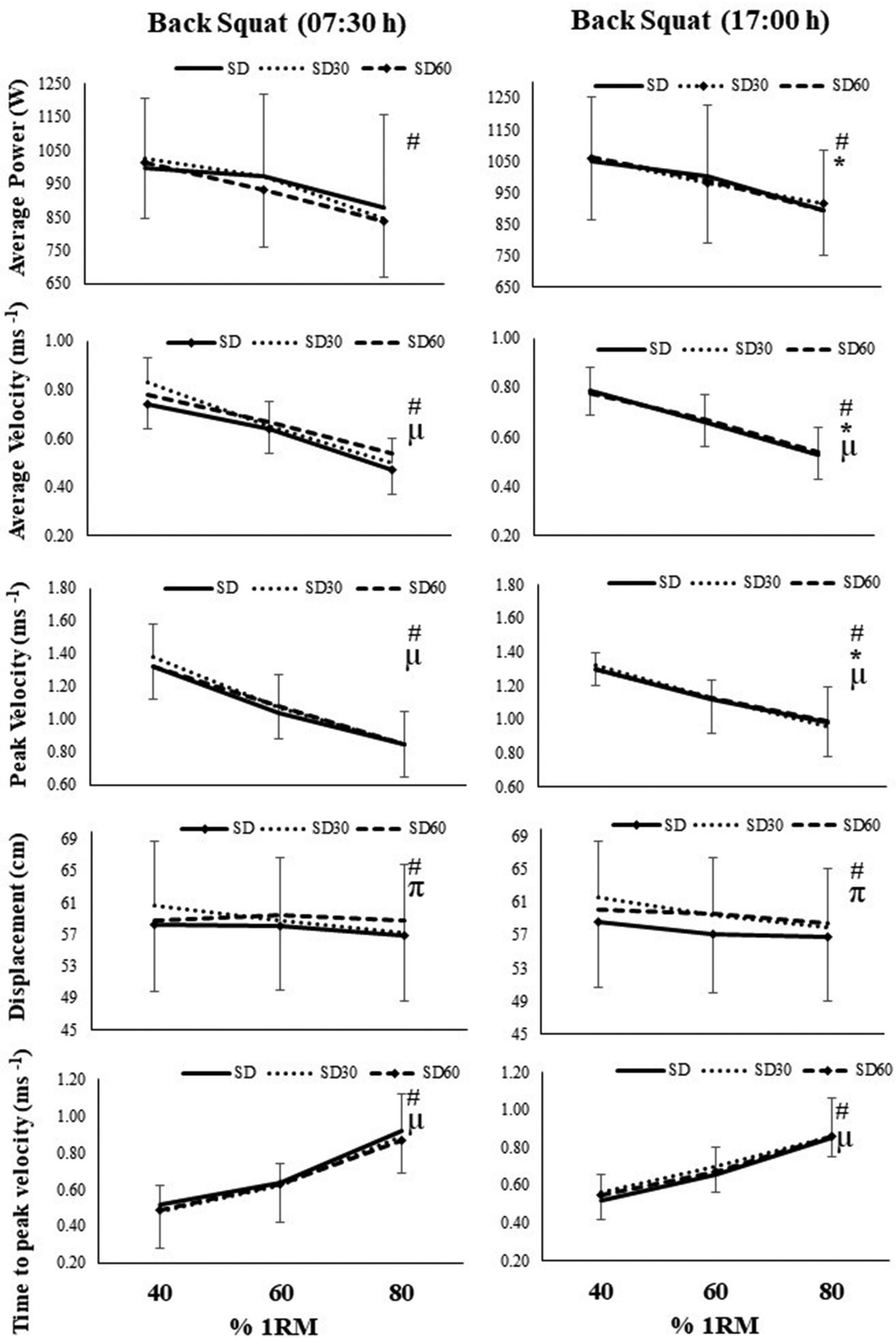

Figure 3. Mean ± SD values of each performance variable for morning (07:30 h) and evening (17:00 h) back squat at 40%, 60% and 80% 1RM loads for the three experimental conditions. # denotes main effect for load, as shown by Bonferroni pairwise comparisons ($P < 0.05$), * main effect for time of day as shown by Bonferroni pairwise comparisons ($P < 0.05$) , π denotes condition and time of day interaction, μ denotes time of day and load interaction denotes.

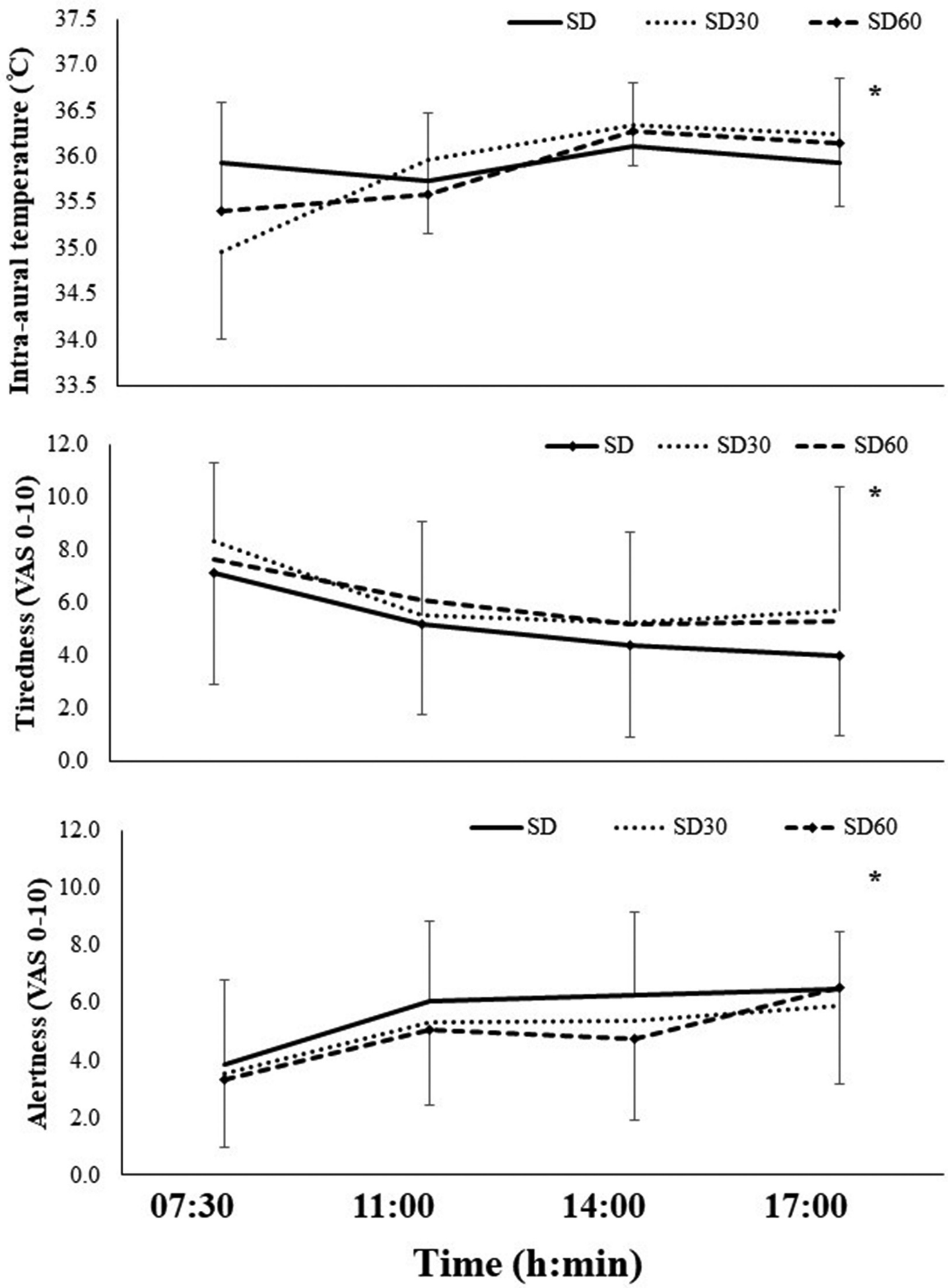

Figure 4. Mean ± SD values for intra-aural temperature, subjective alertness and tiredness recorded at 07:30, 11:00, 14:00 and 17:00 h for the three experimental conditions (PSR_0, PSR_{30}, PSR_{60}). * denotes main effect for time of day as shown by Bonferroni pairwise comparisons ($P < 0.05$).

0.05 ms^{-1}), refer to Figure 3. As expected, there was a corresponding significant main effect of load on subjective effort and RPE values ($P < 0.05$), with 40% of 1RM load eliciting the lower subjective values (Effort: 3.0 ± 0.0; RPE: 9.0 ± 0.0; RPE Breathing: 8.0 ± 0.0; RPE Muscle Fatigue: 9.0 ± 0.0) and 80% producing the highest (Effort: 8.0 ± 0.0; RPE: 15.0 ± 0.0; RPE Breathing: 12.0 ± 1.0; RPE Muscle Fatigue: 15.0 ± 0.0). There was no significant interaction of "condition, time of day and load" for any variable, such that the values across all conditions at both time points for the three loads, rose or fell in the same manner (see Figure 1).

Back squat

There was no significant main effect of nap condition for all back squat performance variables (see Table 1). However, there was a significant main effect for time of day for AP ($P = 0.05$), AV ($P = 0.03$), PV ($P = 0.01$) and RPE ($P = 0.02$), yet no significance of time-of-day for D, tPV or effort, see Table 1. Pairwise comparisons showed that participants had significantly lower AP values at 07:30 h (942.0 W, $P = 0.05$, 95% CI: 845.7–1038.3 W) than at 17:00 h (983.7 W, $P = 0.05$, 95% CI: 879.3–1088.2 W; mean difference: 41.7 W, 95% CI: 0.8–84.2 W, ES = 0.28). There was a significant main effect of "load" on all back squat variables (see Table 1), as anticipated tPV, effort, RPE/breathing/muscle fatigue were significantly lower at 40% and higher at 80% 1 RM ($P < 0.0005$). Conversely, AP, AV, PV and D were significantly highest at 40% and lowest at 80% 1RM ($P < 0.0005$). A significant interaction was present between "condition and time of day" for AV ($P = 0.03$), where values were greater at 17:00 h in the PSR_{60} than PSR_{30} and PSR_0 conditions. There were also significant interactions for "time of day and load" for AV, PV and tPV ($P = 0.03$, $P = 0.02$, $P < 0.05$; respectively), with greater mean values for "load" at 17:00 h compared to 07:00 h. A trend was present for D for "condition and load" interactions ($P = 0.08$; see Table 1 continued).

Physiological and psychological variables (measured at 07:30, 11:00, 14:00 and 17:00 h)

Intra-aural temperature

There was a significant main effect for sleep condition ($P < 0.05$; see Table 2) on intra-aural temperature, with PSR_0 producing the lowest average values (35.51 ± 0.1, 95% CI = 35.21–35.80°C, ES = 0.12), compared to PSR_{30} (36.00 ± 0.1, 95% CI = 35.74–36.27°C, ES = 0.07) and PSR_{60} (36.15 ± 0.12, 95% CI = 35.89–36.42°C, ES = 0.17). There was a significant main effect for time of day ($P = 0.01$, see Table 2) on intra-aural temperature with a drop in temperature between 07:30 h (36.06 ± 0.15; 95% CI = 35.74–36.38°C) and 11:00 h (35.49 ± 0.15; 95% CI = 35.17–35.82°C, ES = 0.30), followed by a progressive rise at 14:00 h (35.92 ± 0.14; 95% CI = 35.63–36.21°C) and 17:00 h (36.07 ± 0.11; 95% CI = 35.84–36.31°C, ES = 0.39), refer to Figure 4.

Tiredness and alertness

There was no significant main effect of nap length on subjective tiredness and alertness ($P > 0.05$, see Table 2), indicating the powernap did not have a significant effect on average feelings of alertness and sleepiness; however, there was a significant main effect on time of day for both variables ($P < 0.0005$). With tiredness being the reciprocal of alertness, as anticipated subjective tiredness values decreased whereas alertness levels increased from 07:30 h (Alertness: 3.6 ± 1.0, Tiredness: 7.7 ± 1.0) to 17:00 h (Alertness: 6.3 ± 1.0, Tiredness: 5.0 ± 1.0), refer to Figure 4. No interaction between "condition and time of day" were identified for tiredness ($P = 0.345$) or alertness ($P = 0.685$) values.

Profile of mood state

Regarding mood, there was no significant effect of condition on all mood profiles, however there was a significant effect of time of day for vigour, happiness, confusion, and fatigue ($P < 0.05$; see Table 2). Vigour and happiness were significantly lower in the morning compared to the evening, whereas tiredness and confusion were significantly higher in the morning than the evening (see Table 2). There was also a trend of time of day for depression ($P = 0.09$; see Table 2); in relation to study aims the time-of-day mood profiles were evident from 07:30 to 17:00 h.

Stroop (word colour interference test)

Colour/not words total. There was a significant main effect of condition ($P = 0.02$; see Table 2), with PSR_0 achieving the lowest total (60.2 ± 2.3; 95% CI = 55.4–65.0, ES = 0.43) with a stepwise increase in PSR_{30} and PSR_{60} (62.8 ± 2.0, 95% CI = 58.5–67.1, ES = 0.25 and 66.8 ± 2.7, 95% CI = 61.1–72.5, ES = 0.48; respectively). However, there was no main effect of time of day or significant interaction (see Table 2).

Colour/not words errors. There was no main effect of condition ($P = 0.59$; see Table 2), but there was a significant main effect of time of day ($P = 0.04$; see Table 2). From 07:00 h (1.4 ± 0.3; 95% CI = 0.9–2.0) to 11:00 h (1.0 ± 0.2; 95% CI = 0.7–1.3, ES = 0.06) there were less errors recorded, however errors increased at 14:00 h (1.0 ± 0.2; 95% CI = 0.6–1.5) and 17:00 h (1.1 ± 0.2; 95% CI = 0.7–1.5, ES = 0.18).

Words/not colours total. There was a significant main effect of condition ($P = 0.045$; see Table 2); pairwise comparisons show that the lowest total score was in the PSR_0 condition (105.6 ± 3.9; 95% CI: 97.3–113.9, ES = 0.03) whereas PSR_{60} achieved the highest total score (110.5 ± 3.2; 95% CI: 103.7–117.3, ES = 0.06). Yet there was no significant main effect of time of day or any interactions between "condition and time of day," see Table 2.

Words/not colours errors

There was no significant main effect of condition or time of day ($P = 0.430$, see Table 2; respectively). There were also no significant interactions for "condition and time of day."

Actimetry variables

There was no significant main effect of condition for any actimetry variables (fell asleep, woke up, actual sleep time, sleep efficiency and fragmentation index; see Table 3), however there was a trend for condition for "woke up" time ($P = 0.06$; see Table 3). There was also no significance main effect of night for any actimetry variables other than "Time in bed" ($P = 0.009$). No significant interactions of "condition and night" were identified (see Table 3).

Stanford sleepiness and waterhouse questions

There was a no significant main effect of condition on subjective sleepiness rating, yet there was a significant time of day effect ($P < 0.05$; see Table 2) where highest values of sleepiness were reported in the morning at 07:30 h (4 ± 0) and lowest levels at 17:00 h (3 ± 0). There was a significant main effect for condition for Waterhouse question 5 ($P = 0.048$; How alert did you feel after 30 minutes of waking?) but for no other questions.

Discussion

We report that following 4 h of partial sleep restriction (PSR) from 02:30 to 06:30 h for two consecutive nights, the implementation of a post lunch nap (30 or 60-min @ 13:00 h), produced no greater benefit on evening performance (maximal or submaximal or perception of effort; see Table 1) compared to a no nap condition, in a cohort of resistance trained males with normal habitual sleep patterns ~8 h. Research into PSR and submaximal performance is scarce, however our findings disagree with those of Brotherton et al. (2019) who employed a similar protocol [2 nights PSR (3 h, 03:30 to 06:30 h), evening sub-maximal weightlifting], and population in terms of strength conditioned (>2 *vs* > 2 years), sleep habits (~8 *vs* ~8 h) and age (22.7 ± 2.5 *vs* 21.6 ± 1.6 years). Where the opportunity to nap for 0 min *vs* 60 min showed an increase in grip strength (2.1%), bench press [8.3% for AP, 6.6 m/s for PV], leg press [4.6% for AP] where $P < 0.05$.

The first fundamental difference between our current work and Brotherton et al. being that Brotherton et al. had a control condition wherein the participants slept 7.5 h (N, retiring at 23:00 and waking at 06:30 h). The partially sleep deprived condition (PSR_0, 3 h per night, 2 consecutive nights) resulted in a decrease in maximal grip strength (2.7%), submaximal values for bench press [AP 11.2%, average force (AF) 3.3% and PV 9.4%] and inclined leg press variables (AP 5.7%) using the MuscleLab linear encoder (Ergotest, version 4010, Norway) when compared to the N condition. Unlike Brotherton et al. we only employed conditions of partial sleep restriction therefore we cannot say if the 4 h PSR for 2 consecutive nights had any effect on performance compared to a normal sleep schedule. This could partially explain the lack of effect between having a nap compared to no nap.

The second fundamental difference is the 1 h difference in sleep restriction protocols (4 *vs* 3 h) which represents a 50 *vs* 37.5% reduction of the participants habitual sleep duration. To the best of our knowledge, no research investigating a potential dose effect of PSR of habitual sleep on submaximal muscular or weightlifting performance has been published, where with more exposure to sleep loss there is a greater impact on performance output (See Silva et al. 2021; Walsh et al. 2021; for recent reviews). As such, there may be a cut off where in our case 50% of habitual sleep taken for 2 nights is tolerated and the homeostatic drive is not affected by a 30 or 60-mins nap compared to no nap. Belenky et al. (2003) employed four sleep conditions (3, 5, 7 and 9 h per night, 7 consecutive nights) and reported sleep restriction of 5 and 7 h resulted in declines to performance which stabilised after day two. Those severely sleep restricted (3 h) had continual reductions in performance for the 7-day duration. They concluded approximately 4 h is the minimum sleep duration per night to achieve a state of equilibrium, that enables an individual to maintain a "stable" level of alertness and performance, yet <4 h results in decrements. Although this agrees with the hypothesised dose response of sleep restriction to performance, this study measured performance using a psychomotor vigilance test and did not measure sporting performance. Habitual sleep of participants was also not reported; therefore, we are unaware of whether the participants regularly had restricted sleep and would not be as sensitive to those who achieve optimal sleep.

Lastly, the lower body exercise chosen (inclined leg press *vs* back squat) differed between that of Brotherton et al. (2019) and our study. Brotherton et al. reported poor sensitivity in leg press versus bench press to partial sleep restriction compared to normal sleep. It has been suggested previously that more "skill-orientated" lifts with a high cognitive component (such as bench press) may be more affected by sleep loss compared to less skill-orientated such as leg press. Deterioration in cognitive tasks after 13:00 h has been attributed to (**i**) an

Table 3. Mean ± SD, F values and P values for all actimetry and Waterhouse questionnaire variables measured in the study. **Bold** values indicate significant figures; *italic* indicates a trend ($0.1 < P > 0.05$).

Actimetry variables	SD	SD_{30}	SD_{60}	Significance condition	Significance night	Significance interaction
Fell asleep (h:m)	02:10 ± 0:23	02:31 ± 0:24	02:27 ± 0:17	$F_{1.9, 26.6} = 1.69$ ($P = 0.205$)	$F_{1.0, 14.0} = 0.50$ ($P = 0.491$)	$F_{2.0, 28.0} = 0.04$ ($P = 0.966$)
Time in bed (h:m)	04:15 ± 0:32	04:16 ± 0:29	04:19 ± 0:17	$F_{1.4, 20.2} = 0.18$ ($P = 0.769$)	**$F_{1.0, 14.0} = 9.09$ ($P = 0.009$)**	$F_{1.4, 19.2} = 1.30$ ($P = 0.284$)
Woke up (h:m)	06:18 ± 0:46	06.30 ± 0:36	06:24 ± 0:14	*$F_{2.0, 28.0} = 3.11$ ($P = 0.060$)*	$F_{1.0, 14.0} = 1.55$ ($P = 0.233$)	$F_{1.3, 18.4} = 1.78$ ($P = 0.201$)
Actual sleep time (h:m)	03:22 ± 0:27	03:23 ± 0:28	03:26 ± 0:17	$F_{2.0, 28.0} = 0.26$ ($P = 0.770$)	$F_{1.0, 14.0} = 0.04$ ($P = 0.848$)	$F_{2.0, 28.0} = 2.41$ ($P = 0.108$)
Sleep Efficiency (%)	80.2 ± 2.1	79.9 ± 2.3	78.4 ± 2.6	$F_{2.0, 28.0} = 0.33$ ($P = 0.721$)	$F_{1.0, 14.0} = 2.45$ ($P = 0.140$)	$F_{1.1, 15.4} = 1.47$ ($P = 0.247$)
Fragmentation Index (%)	29.6 ± 2.9	24.0 ± 3.6	23.2 ± 2.6	$F_{2.0, 28.0} = 1.35$ ($P = 0.275$)	$F_{1.0, 14.0} = 0.118$ ($P = 0.737$)	$F_{2.0, 28.0} = 0.53$ ($P = 0.597$)
Waterhouse Questionnaire						
How easily did you get to sleep?	0.3 ± 3.3	0.3 ± 4.2	−1.3 ± 3.2	$F_{1.5, 21.1} = 1.823$ ($P = 0.191$)		
What time did you get to sleep?	1.9 ± 2.9	1.7 ± 3.7	1.7 ± 3.8	$F_{2.0, 28.0} = 0.35$ ($P = 0.966$)		
How well did you sleep?	0.5 ± 2.7	−0.7 ± 2.2	0.6 ± 2.5	$F_{2.0, 24.6} = 2.330$ ($P = 0.116$)		
What was your waking time?	−3.1 ± 1.5	−3.5 ± 2.1	−3.5 ± 1.9	$F_{2.0, 28.0} = 0.499$ ($P = 0.612$)		
How alert did you feel after 30 minutes of waking?	−2.3 ± 2.6	−2.3 ± 2.0	−0.6 ± 3.2	**$F_{2.0, 28.0} = 3.402$ ($P = 0.048$)**		

increase in circulation of catecholamines in the blood hence increased arousal, **(ii)** the homeostatic drive due to time awake and/or mental fatigue (Carrier and Monk 2000; Reilly and Edwards 2007). Therefore, back squat was chosen due to the greater cognitive component required to execute the exercise compared to inclined leg press; hence we anticipated submaximal back squat would be inhibited more under conditions of partial sleep restriction.

To explain the underlying processes of sleep regulation, mathematical models based on physiological processes have been developed to account for circadian, ultradian and homeostatic components. These models address: (1) the homeostatic component accountable for greater sleep propensity, during waking and the dissipation during sleep; (2) circadian processes, independent of prior sleep, that define the alternating periods from high to low sleep propensity; (3) ultradian processes that occurs within the sleep episode and represents shifts from nonREM to REM sleep states (Borbély and Achermann 1992; Brotherton et al. 2019). Models representing these processes have been extensively reviewed and become an important approach for many experiments, providing a conceptual framework for analysis of data (Achermann and Borbély 2003). Proposed models have been used to predict cognitive performance, effects of partial sleep restriction and daytime napping (Borbély and Achermann 1992; Rempe et al. 2010). The framework readily explains why the PSR_0 condition reported greater test errors in the word colour interference test, compared to retiring for a nap, as the homeostatic component increases due to time since awake and inhibits cognitive function; those able to retire for a nap had the opportunity to sleep which allowed the accumulated homeostatic pressure to dissipate, lowering sleep propensity post nap.

In contrast to previous research, there was a significant effect of condition for intra-aural temperature but not for subjective ratings of tiredness or alertness. These results may be due to method of measurement error, as intra-aural is not considered an accurate or robust measure compared to methods such as rectal and gut sites. Previous literature has shown alertness and fatigue are closely influenced by body temperature and time since awake, with alertness and temperature showing a causal link, and fatigue producing inverse values to these (Edwards and Waterhouse 2009). When partially sleep deprived, a transient fall in temperature and alertness would be expected around 12:00–14:00 h, often referred to as the "post lunch dip." Ratings of alertness would expectedly increase, and tiredness decrease, post nap, as reported by Waterhouse et al. (2007). Our findings may have been influenced by sleep inertia, due to post nap measures being taken immediately after waking. Although a 30-minute nap is said to avoid sleep inertia, it is dependent on the individual and prior wake/sleep (Hilditch et al. 2017). In agreement with previous literature, we did report a significant time of day effect for intra-aural temperature, with highest values at 17:00 h, coinciding with greater muscle force production (Robertson et al. 2018), and a significant time of day effect for tiredness and alertness. Ratings of tiredness were lowest at 14:00 h and slightly increased at 17:00 h, whereas alertness values increased from 14:00 to 17:00 h. Higher alertness values at 17:00 h may have contributed to greater evening performance as mood and motivation have shown to be a contributing factor to muscle force output (Brotherton et al. 2019).

Unlike the work of Brotherton et al. the current study employed morning and evening physical performance tests. A significant effect for time of day were reported, with increases from morning to evening for left- and right-hand grip strength (5.6% and 3.9%, respectively) bench press (7.6% for AP) and back squat [4.4% (AP), 3.6% (AV), 5.1% (PV); $P < 0.05$]. Although we did not have a normal sleep condition our findings agree with Robertson et al. (2018), who conducted exercise sessions at 07:30 and 17:30 h using a Musclelab linear encoder, with mass ranges from low to high on the bar. They reported diurnal variation in submaximal muscle strength measures with increases in AF and PV from morning to evening in bench press (2.5 and 12.7%) and back squat (1.9 and 8.3% difference). This is consistent with existing literature that has shown greater muscle force output is aligned with the daily peak of core temperature (15:00–18:00 h; Edwards and Waterhouse 2013; Reilly and Waterhouse 2009). Our data demonstrates that independent of the participants receiving habitual or partial restricted sleep in the nights prior to performance, we can detect diurnal variation for submaximal performance.

As expected, a significant main effect for "load" was present for all bench press and back squat output variables (AP, D, AV, PV, tPV; see Table 1). From 40 to 80% 1RM, where there was greater load against the movement, tPV increased yet PV, AV, AP and D (See Figure 2) were highest when the load on bar was lowest (40% 1RM). These findings are consistent with the fundamental force-velocity properties of skeletal muscle and have been demonstrated previously during complex movements, using MuscleLab linear encoders and force platforms systems to investigate diurnal variations in submaximal loads (Ammar et al. 2018). In agreement with previous research, tPV increased under greater resistance as it takes longer for the participant to generate and produce power to execute the movement. However, our findings for AP disagree with previous studies as this variable should increase under higher loads as it requires greater force production to execute the movement (Ammar et al. 2018; Brotherton et al. 2019; Robertson et al. 2018).

Interactions of "load and condition" were not present for any performance variables. It has previously been demonstrated that MuscleLab force-velocity linear encoders, which we have used, are sensitive to diurnal variation during bench press and back squat movements, under low to high masses. Our findings further demonstrate this with significant interactions for "time of day and load" for back squat values of AV, PV and tPV ($P = 0.032$; $P = 0.022$; $P = 0.004$, respectively). Both AV and PV were 9.6% and 15.3%, respectively, greater at the highest load (80% of 1RM) in the evening compared to morning values. Literature suggests that to achieve performance enhancement an athlete should train at a load comparable to maximal power output which is approximately 70–80% of 1RM, according to some studies, hence the reason we employed 40, 60 and 80% 1RM as our protocol (Ammar et al. 2018).

For indication of cognitive performance, we reported a significant main effect of condition for the word colour interference test (See Table 2), yet no significance of condition for subjective mood states. In the PSR_{30} and PSR_{60} conditions, the total word colour interference score (number of answers) was significantly greater (with no change in number of errors) than those who had no nap (PSR_0). The PSR_{60} condition also had a greater total score when compared to PSR_{30} condition, where longer nap duration improved word colour interference accuracy (See Table 2). There was greater number of errors in the early morning (07:30 h) for the word colour interference test for response of colours rather than words, this corresponds with higher subjective ratings of alertness in the early morning that decrease throughout the day. There was also a significant time of day effect for vigour, confusion, fatigue, and happiness for values of mood states, with fatigue and confusion decreasing throughout the day and vigour and happiness increasing, with greatest ratings at 17:00 h. Previous research has shown that naps are able to counteract fatigue and improve subjective ratings of cognition, vigilance and psychomotor ability (Lovato and Lack 2010). When sleep restricted the time since awake component is greater and the corresponding elevation of subjective fatigue values in the late afternoon are likely to result in impaired function (Monk 2005). By implementing the nap, our results suggest the nap, offset symptoms and improved cognitive variables by reducing sleep propensity and decreasing the number of test errors. Cognitive variables follow a circadian rhythm, with function typically low in the morning and peaking in the evening (Edwards et al. 2021; Van Dongen and Dinges 2000). The improvement in cognitive ability post nap reductions is often said to be dependent on sleep stages that occur, as the quantity of slow wave sleep and rapid eye movement (REM) differ based on the nap duration (Ficca et al. 2010). As we did not use polysomnography, we are unable to report information on sleep stages; further research must ensure measures of sleep stages are taken to see if the findings coincide with specific sleep stages.

Limitations

Throughout the three experimental conditions dietary intake was not assessed or recorded and therefore we cannot ensure consistency across the study. When partially sleep deprived, impulse control is altered and previous findings have shown that it is common to consume significantly greater caloric intake, which is associated with altered leptin and ghrelin hormone responses. It is possible that participants may have consumed greater dietary intake during experimental conditions and therefore impacted their performance output and cognitive function. Another limitation of the current study was the absence of a control condition; however, the current protocol was already very demanding for all those that participated. Previous research by our working group has reported diurnal variation after employing normal sleep protocols, hence our choice to not include a condition with no sleep restriction. Lastly, participants were given the opportunity to nap for 30 or 60 minutes at 13:00 h in two of the experimental conditions, yet no measures were taken during the "nap" period and therefore the quality of the nap was subjectively reported afterwards. If we had used a technique such as polysomnography, sleep stages and sleep duration could have been measured; allowing us to further understand the mechanisms and effectiveness of a nap.

Summary

Results obtained from this study indicate that 4 h of PSR, for two consecutive nights, did not have a significant effect on submaximal performance, for measures of bench press and back squat (AV, AP, tPV, PV, D; $P > 0.005$). Despite this, we did report that a post lunch nap of 30- and 60-minute durations improved mood state, cognitive function, and reduced tiredness. As shown in previous research, neurobehavioral deficits are often reported following restricted sleep. It is hypothesised that the opportunity to nap provides temporary relief from excessive tiredness and allows the accumulation of homeostatic pressure to dissipate, however the exact mechanisms of action are yet to be investigated. Implementing a nap at 13:00 h did not improve physical performance variables compared to the PSR_0 condition; these findings hold important questions regarding the optimal nap duration and timing, when considering prior sleep. As previously discussed, there is a potential dose response for sleep restriction and performance, therefore having a nap following 4 h of PSR, may not be beneficial as the individual has had enough sleep to perform submaximal lifts. These findings will be of interest to athletes who are partially sleep restricted and are unable to nap due to time constraints.

Practical implications

To the authors knowledge this is one of the few studies to investigate partial sleep restriction, and the effects of submaximal weightlifting performance, using linear position technology, and cognitive functions relating to time of day. The current findings may therefore provide important recommendations and interventions for athletes who have high training/competition demands and are facing partial sleep restriction. Despite this, based on our results, the effectiveness of a nap is dependent on the amount of sleep restriction, the opportunity to nap and likely the nature of the sport. For example, a nap intervention may prove beneficial for sleep restricted athletes competing in skill-based sports, that require greater cognitive performance and time on task.

Further work should investigate the mechanisms of a nap, which would provide greater insight into optimal nap duration and the effectiveness of implementing a nap on performance. In a population of healthy, motivated and resistance trained males, 4 h partial sleep restriction for two consecutive nights, was not sensitive to detect any significant effect on submaximal performance.

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